University of Southern California

Corona Discharge Ignition for Advanced Stationary Natural Gas Engines

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COOPERATIVE AGREEMENT DE-FC26-02NT41336

Awarded 4/1/03, 36 Month Duration

$710,491 Total Contract Value ($560,491 DOE)

Objectives

- **Integrate pulsed corona discharge ignition system into stationary natural gas engines**
  - 1998-2002 Ford Ranger, 2.5L SOHC 4-cylinder engine, 2 plugs per cylinder (1 conventional plug, 1 corona ignition port)
  - TBD large-bore stationary natural gas engine
- **Determine if the ≈3x shorter burn times attainable with pulsed corona discharges (already demonstrated in laboratory apparatuses with CH_4-air mixtures) apply to NG engines also**
- **If so, exploit the shorter burn times**
  - (Simplest approach) Leaner mixtures (lower NO_x)
  - (More difficult) Higher compression ratios + water injection (higher efficiency with same NO_x)
  - (Most difficult) Redesign intake port and combustion chamber for lower turbulence since the same burn rate is possible with lower turbulence (reduced heat loss to walls, higher efficiency)
- **Assess the possibility for NO_x reduction using additional discharges during the exhaust stroke**

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Project Schedule

- 0 - 12 months
  - Design, build and evaluate corona discharge ignition system for IC engines
    - Corona electrode
    - Ignition control system
  - Conduct baseline spark plug tests at USC using existing engine
  - Conduct lean-burn testing with corona ignition at USC (single cylinder corona ignition; other cylinders conventional ignition)
  - Conduct baseline spark plug tests at GEC using existing engine
  - Adapt corona ignition system for use in GEC 14-liter engine
- 13 - 24 months
  - Conduct lean-burn testing with corona ignition at USC (all cylinders corona)
  - Test feasibility of NOx reduction using post-burn corona discharges (USC)
  - Adapt USC engine test facility to accommodate water injection
  - Conduct water injection tests at USC
  - Conduct lean-burn tests at GEC
  - Start water injection tests at GEC
- 25 - 36 months
  - Complete water injection tests at GEC, including elevated compression ratios
  - Test feasibility of NOx reduction using post-burn corona discharge (GEC)
  - Retrofit USC engine for low-turbulence operation
  - Conduct feasibility study of corona-ignited low-turbulence engine at USC
  - Conduct feasibility study of corona-ignited low-turbulence engine at GEC
  - Prepare final reports and manuscripts for archival publication

Accomplishments

- Refurbished USC Engine Laboratory - Labview control and data acquisition, dynamometer, Horiba emissions bench
- Built and tested corona discharge ignition engine mockup
- Tested ignition of flame by corona & arc discharges at high pressure
- Tested discharge efficiency of corona & spark discharges
- Developed semi-optimized electrode design

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Technical approach - Flame ignition by pulsed corona discharges

- **Characteristics**
  - Initial phase of spark discharge (< 100 ns) - highly conductive (arc) channel not yet formed
  - Multiple streamers of electrons - multiple ignition sites with one electrode & one discharge generator
  - High energy (10s of eV) electrons - couple efficiently with cross-section for ionization, electron attachment, dissociation
  - More efficient use of energy deposited into gas
- **Enabling technology: USC-built discharge generators having high wall-plug efficiency (>50%) - far greater than arc or laser sources**

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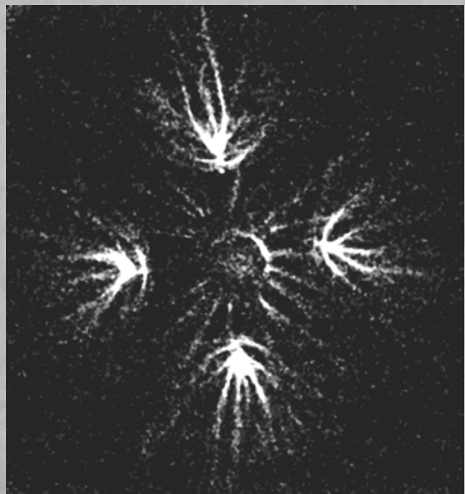
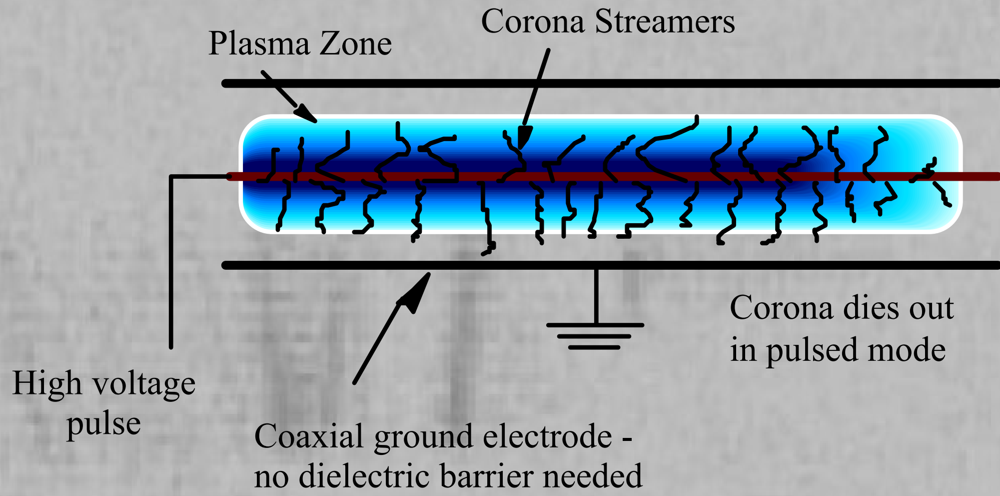
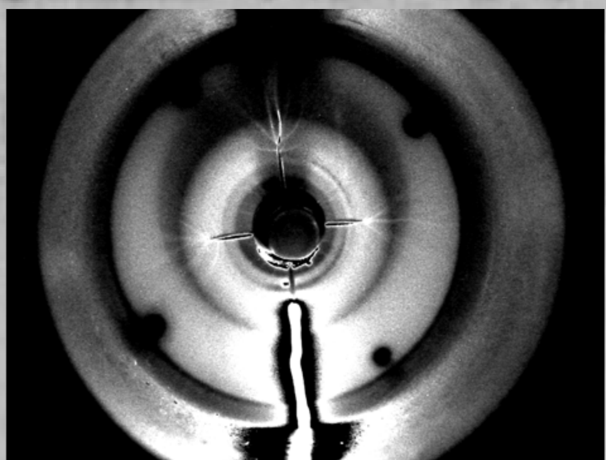
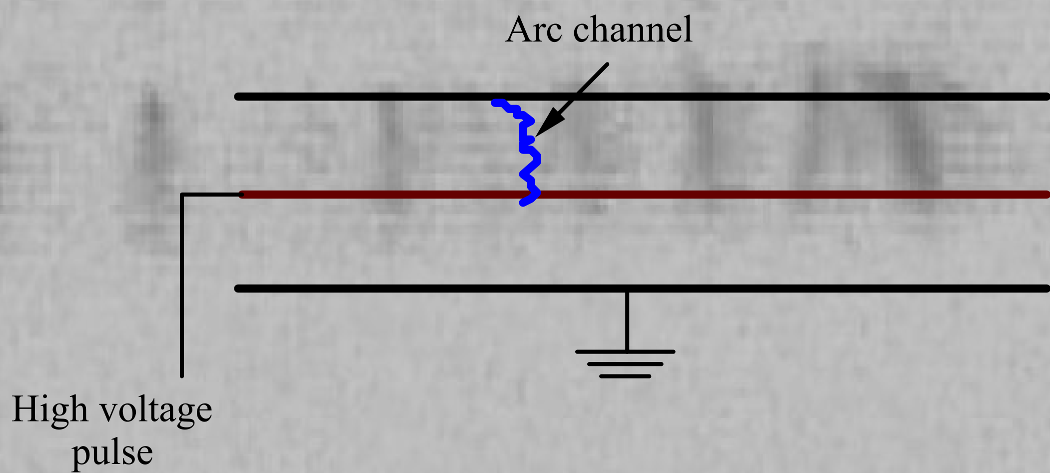
Corona vs. arc discharge





Corona phase (0 - 100 ns)

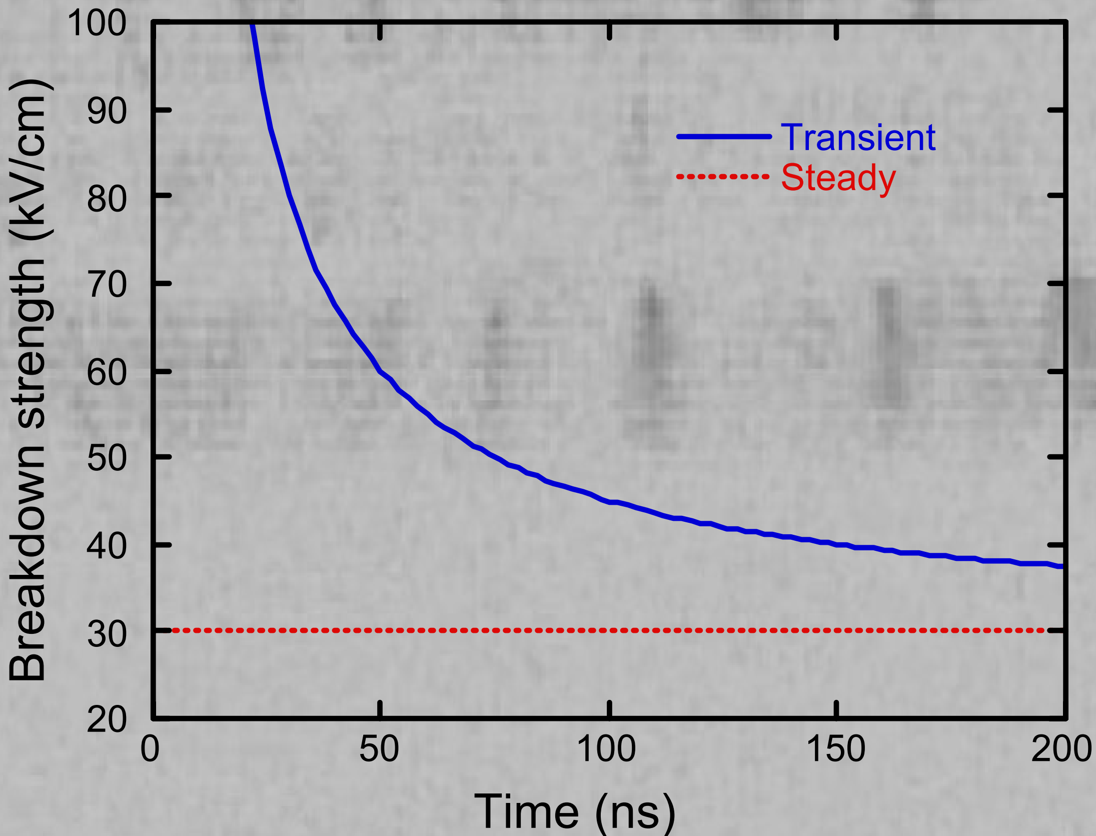




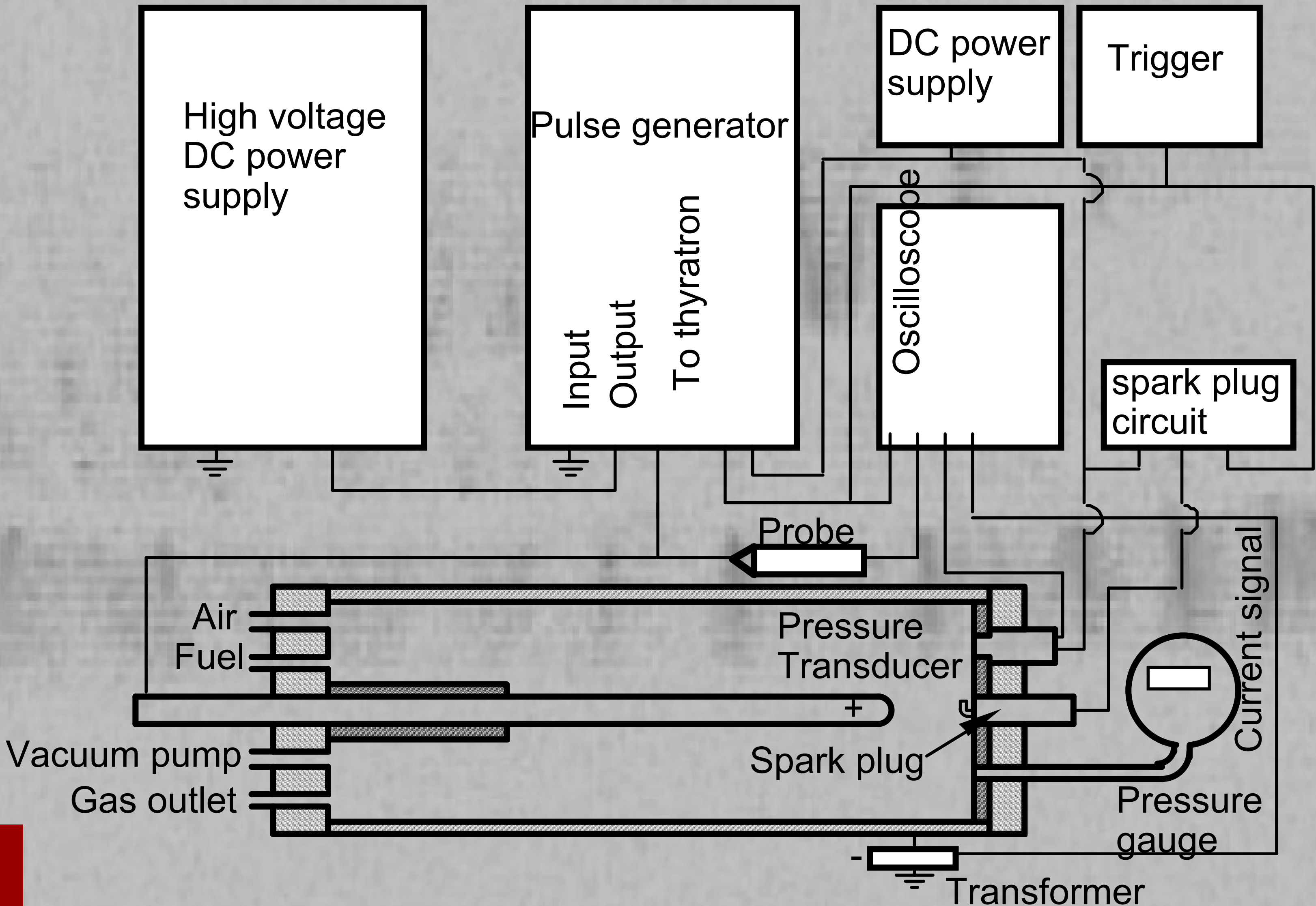
Arc phase (> 100 ns)

Corona vs. arc discharge

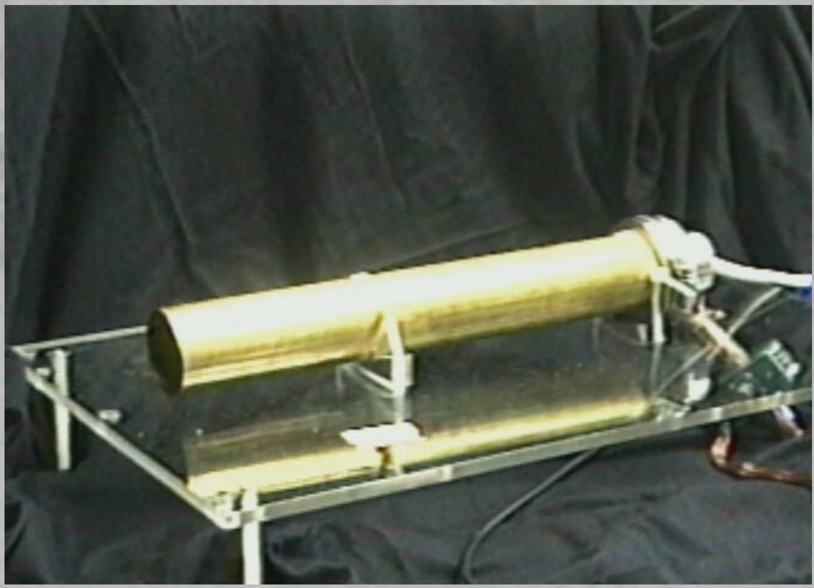
- For short durations (1's to 100's of ns depending on pressure, geometry, gas, etc.) DC breakdown threshold of gas can be exceeded without breakdown ***if high voltage pulse can be created and stopped quickly enough***

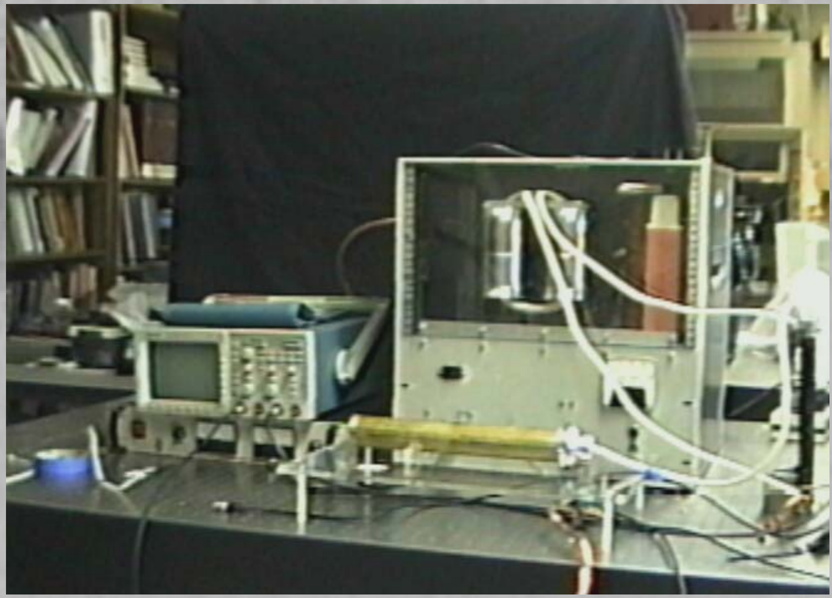


Experimental apparatus for corona ignition feasibility testing (constant volume)



Apparatus for corona ignition





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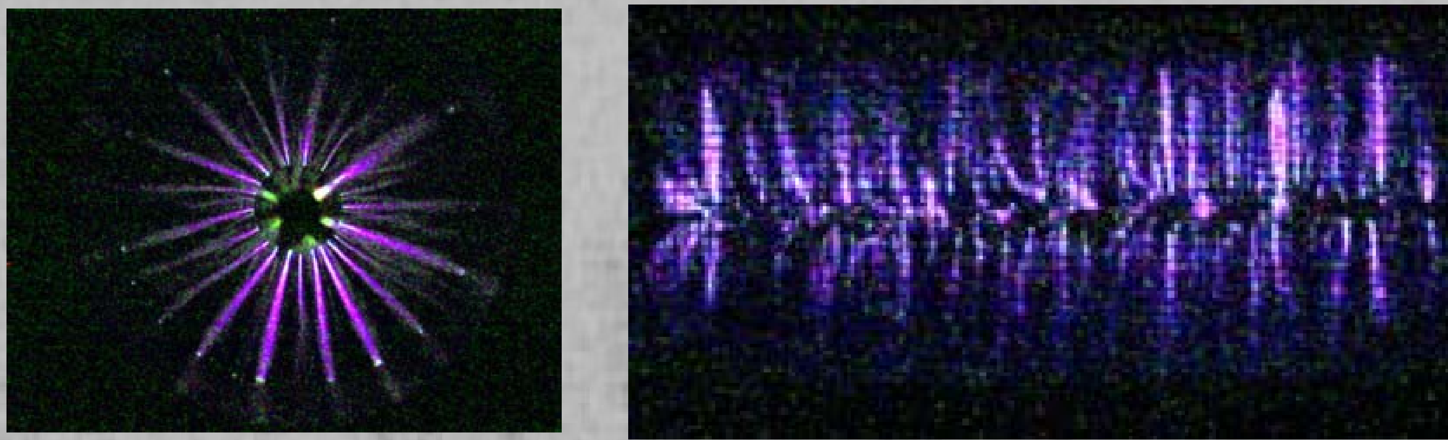
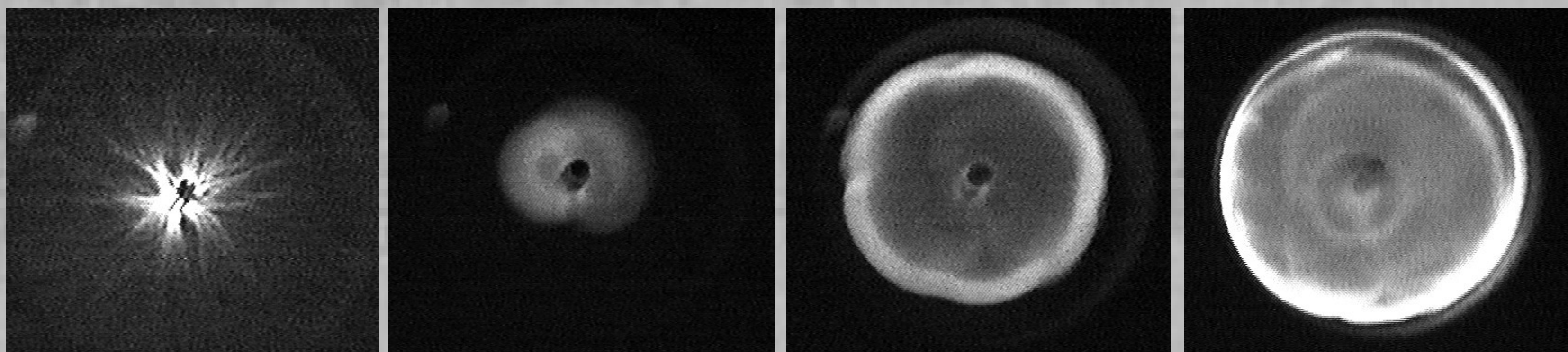
Images of corona discharge & flames

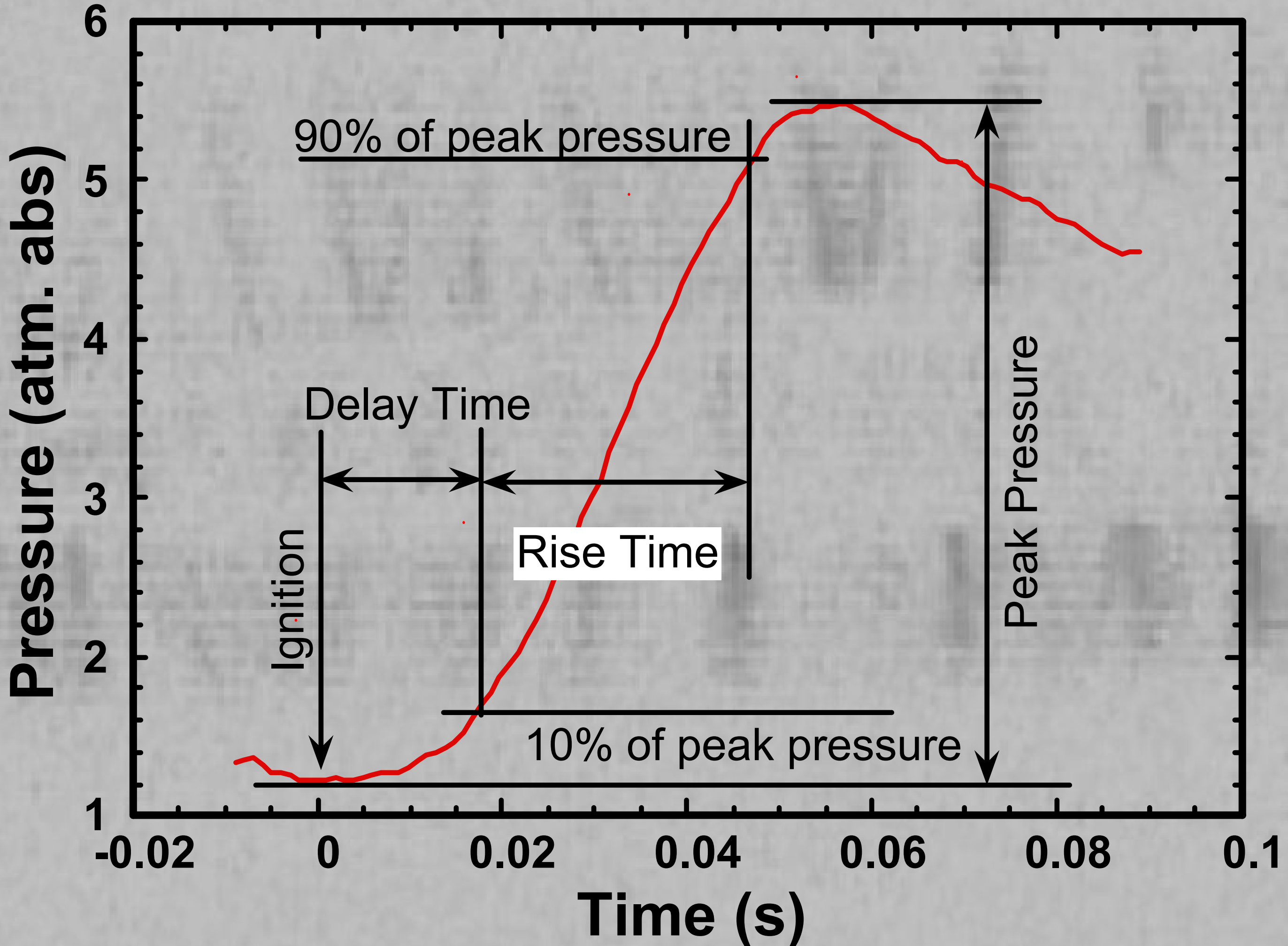


Axial (left) and radial (right) views of discharge

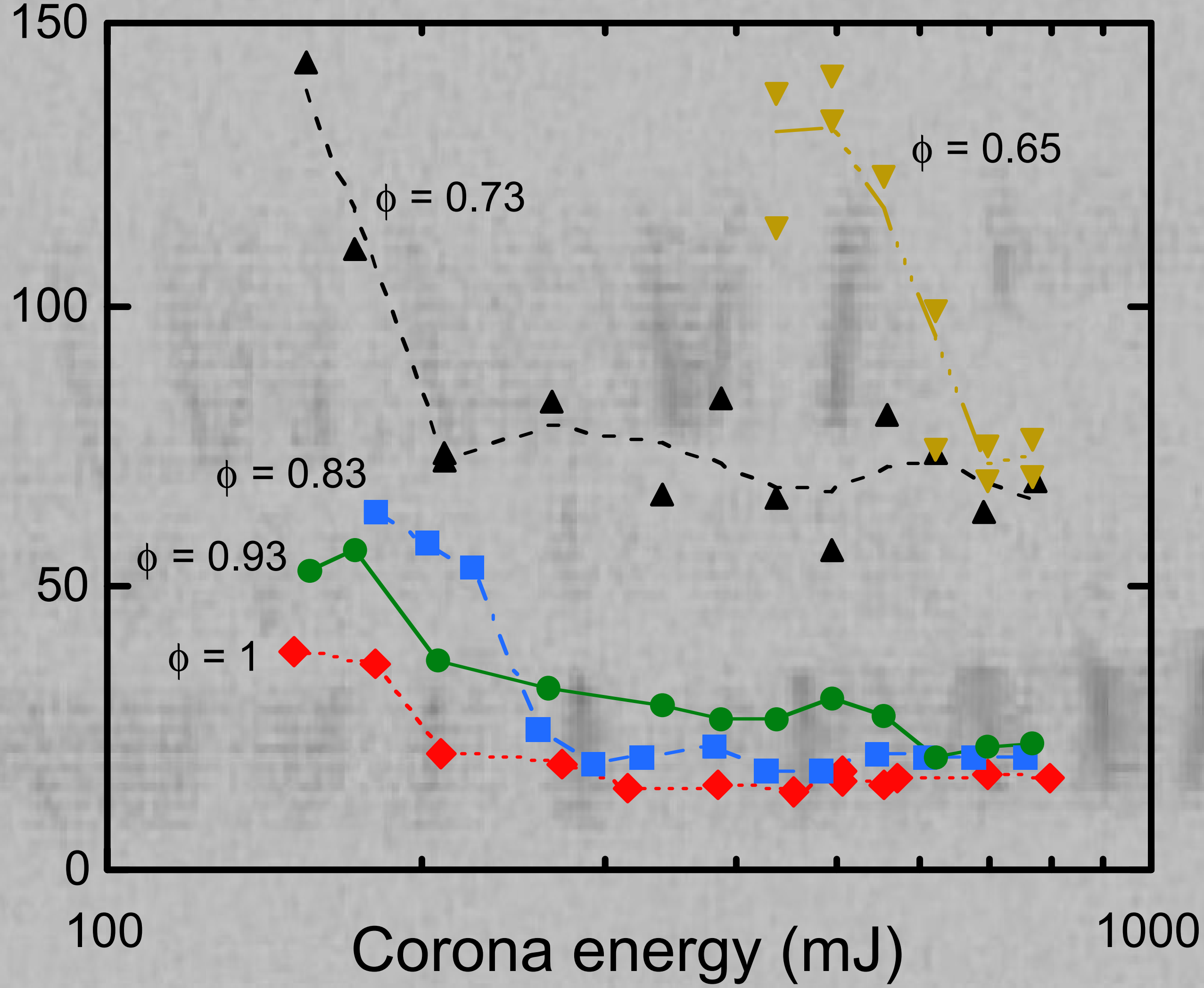


Axial view of discharge & flame
(6.5% CH_4-air, 33 ms between images)

Definition of delay and rise time for comparing ignition methods



Results



"Optimal" energy above which ignition properties are nearly constant

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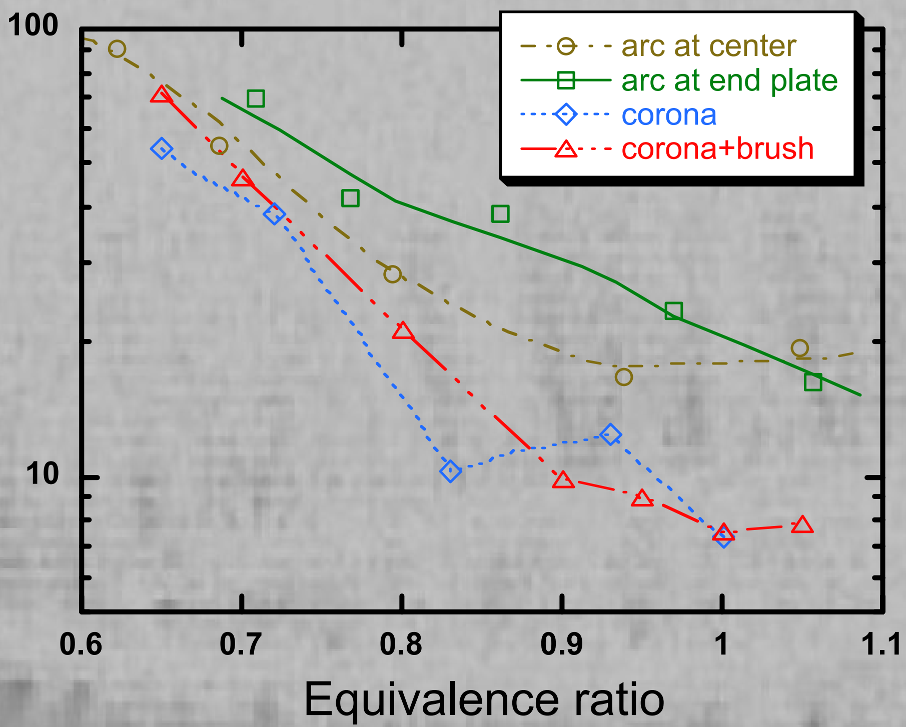
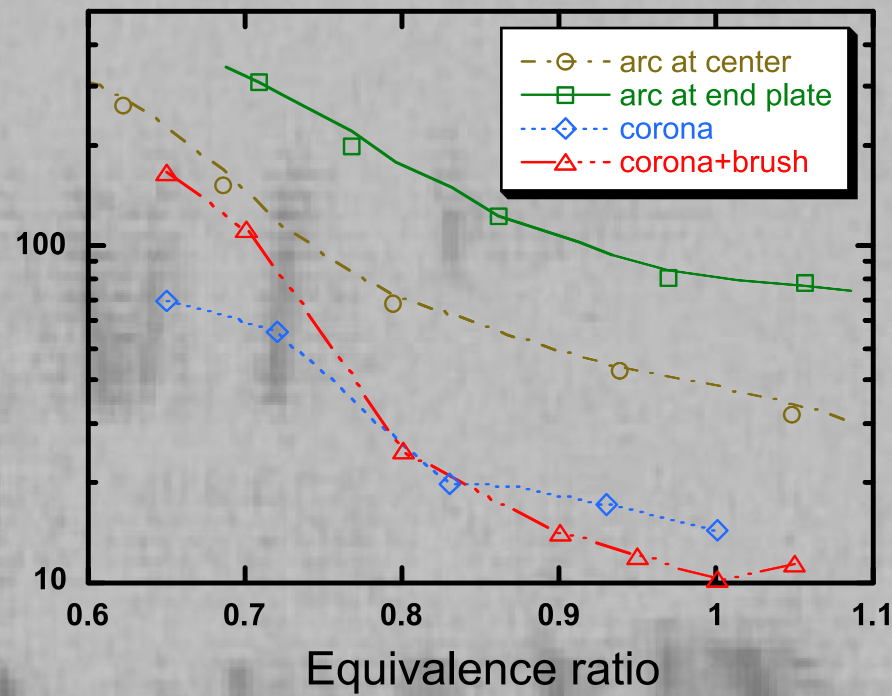
Ignition delay & rise time (methane-air)





- **Both ignition delay time (0 - 10% of peak P) & rise time (10% - 90% of peak P) ≈ 3x smaller with corona ignition**
- **Rise time more significant issue**
  - Longer than delay time
  - Unlike delay time, can't be compensated by spark advance
- **"Brush" electrode provides localized field strength enhancement with minimal increase in surface area (⇒ heat loss)**

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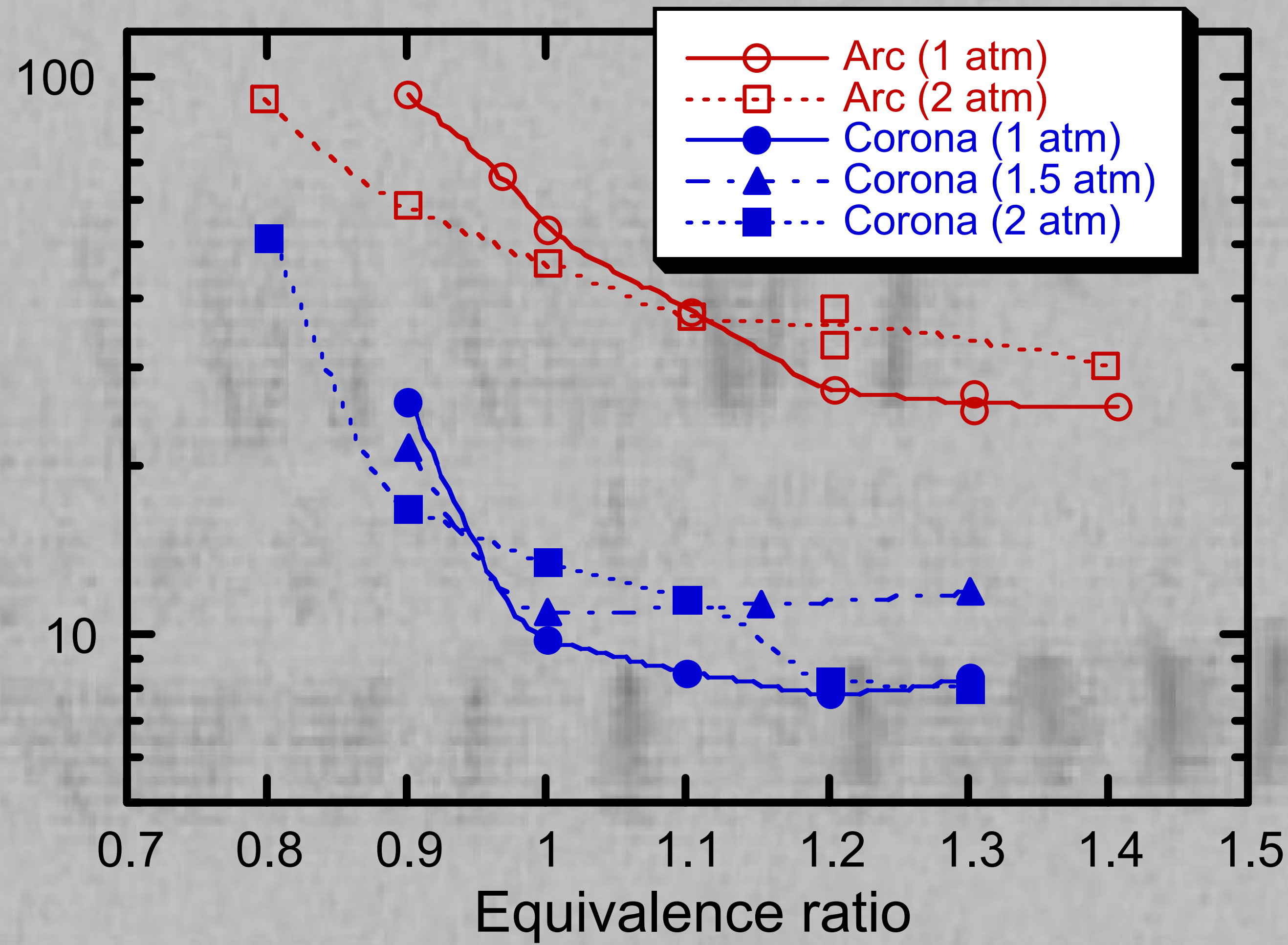
Pressure & fuel effects - propane-air



Results similar at higher pressure and with other fuels

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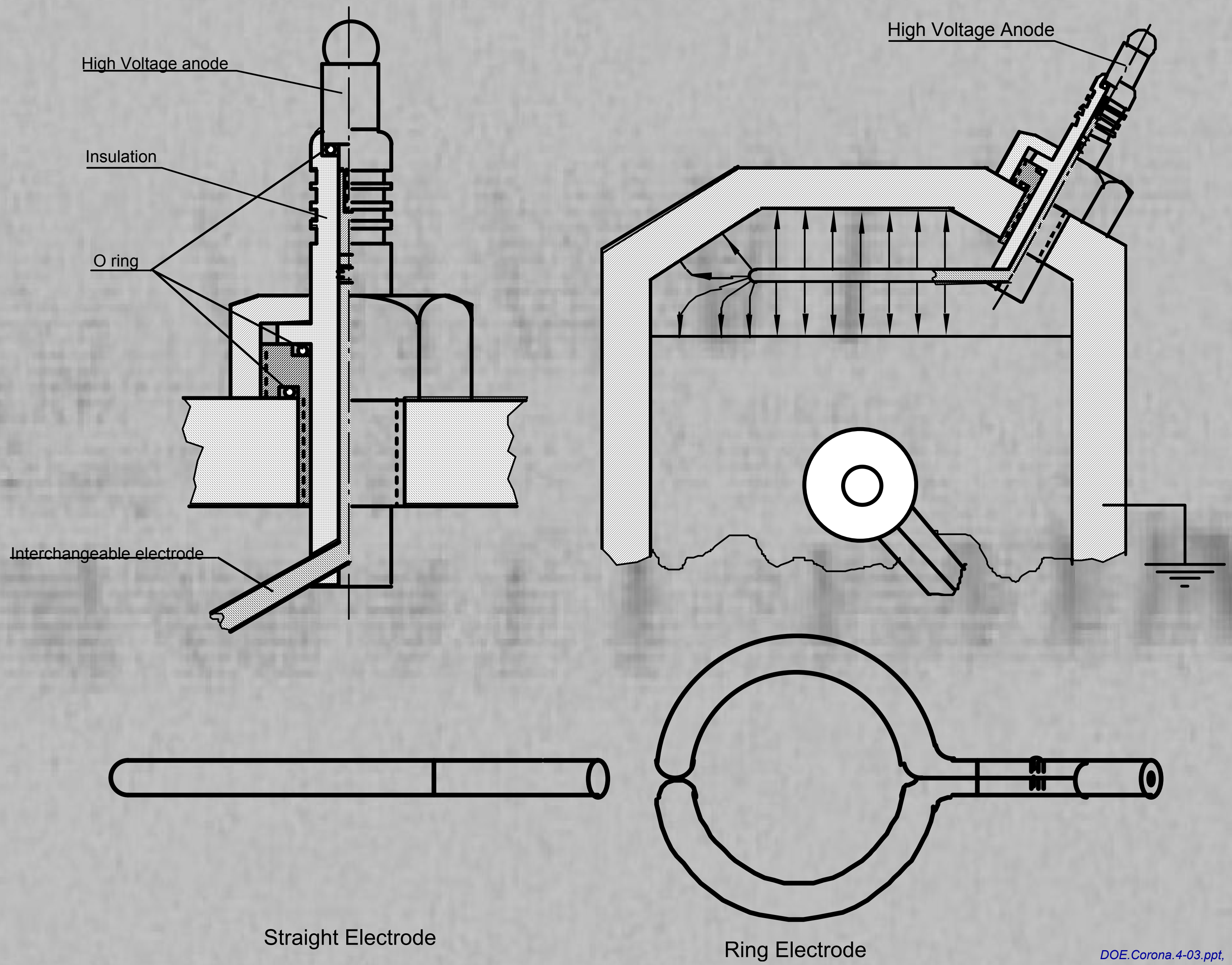
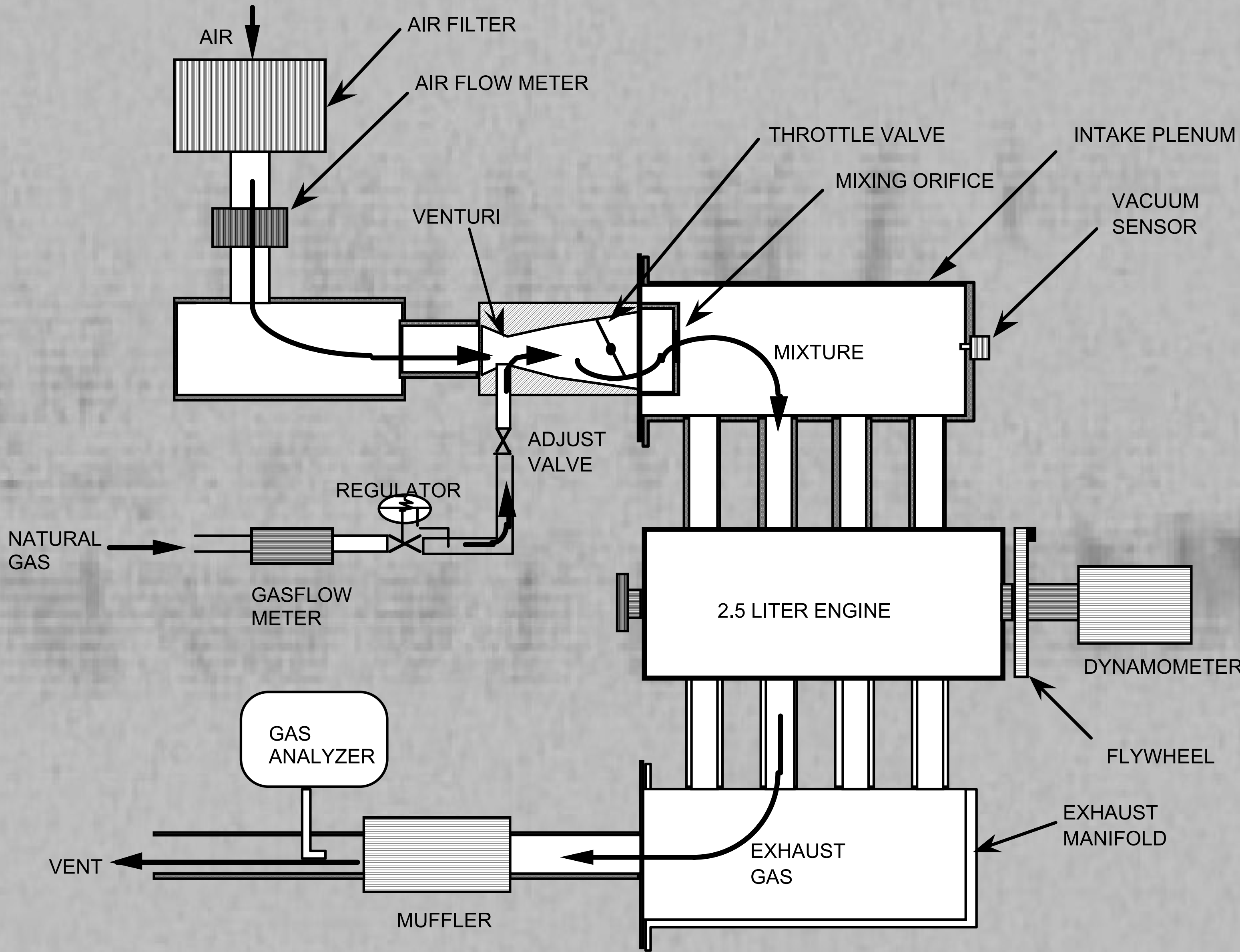
Pulsed corona discharges for NG engines



USC IC engine test facility



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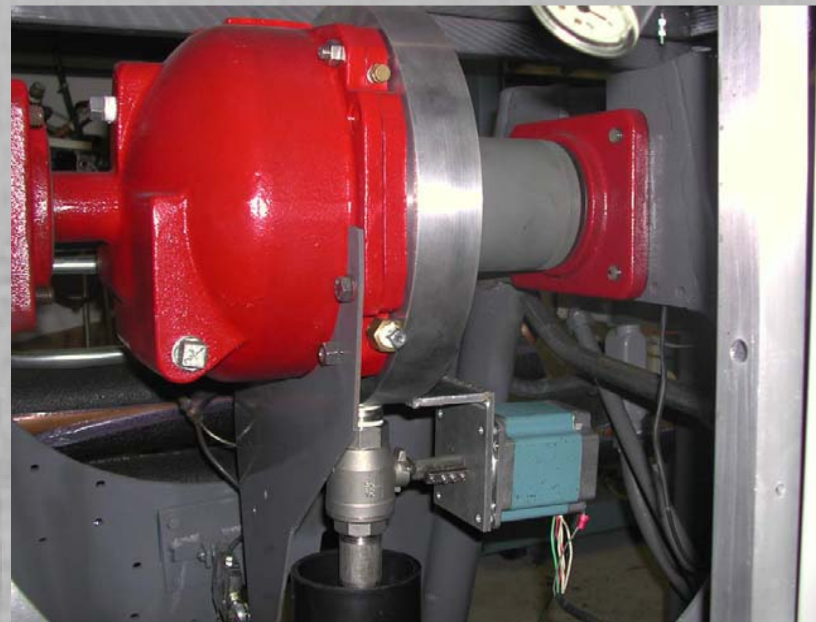
USC engine lab



USC Engine Lab Upgrades

- Modify dynamometer for stepper motor control
- Upgrade data acquisition hardware to National Instruments
- Upgrade software to LabView
- Various upgrades to Horiba emissions bench
- Run all wires in conduit to reduce EMF noise
- Use terminal blocks for reliable connections
- Install flow meter on each fuel injector
  - Allows different fuel flows to each cylinder
  - Can test corona ignition in one cylinder at different conditions than in other (driving) cylinders

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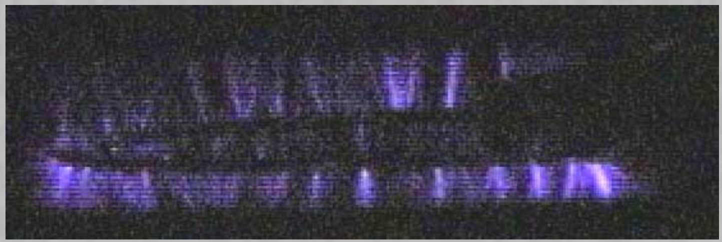
Development of corona ignition for IC engines

- **Test fixture built to same dimensions as engine cylinder and piston crown at TDC to test corona in this geometry**
- **Enables initial testing of electrode geometries and visualization of corona**
- **Allows optimization of electrode geometries and discharge conditions before conducting on-engine testing**
- **Corona streamers from ring electrode to upper and lower plates can be seen**



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Corona discharge movies

QuickTime™ and a Cinepak decompressor are needed to see this picture.

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Top view **Side view**

- **All shots at identical conditions, at borderline arcing condition**
- **Corona discharge present in every shot**
- **When followed by arc discharge, noise & light emission increase substantially with little increase in discharge energy**

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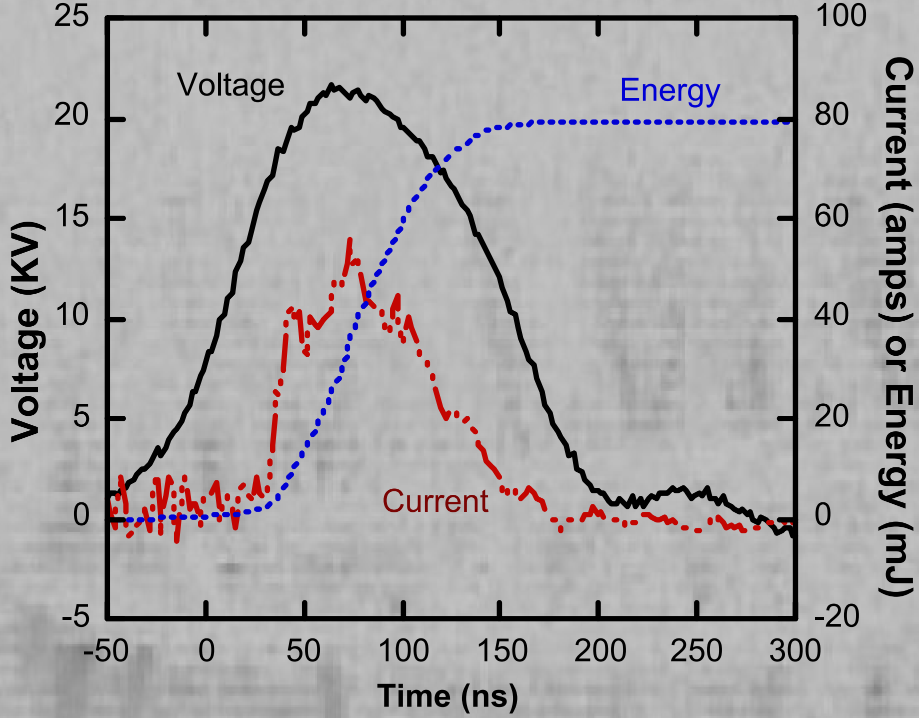
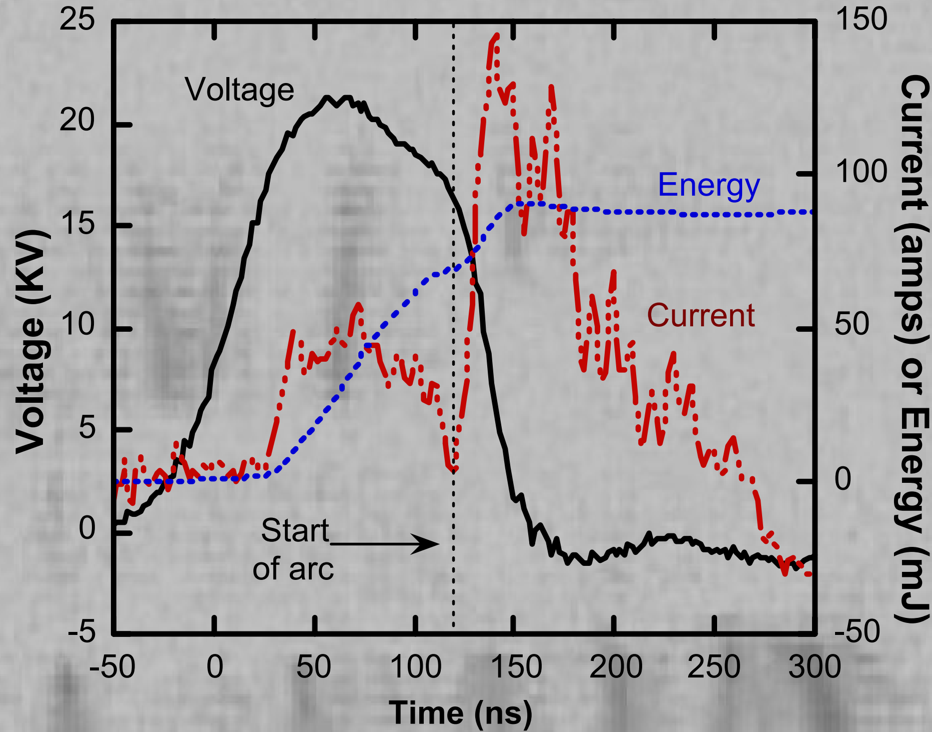
Characteristics of corona discharges



Corona only (1 atm)



Corona + arc (1 atm)

- **Current flows when voltage exceeds ≈ 15 kV**
- **If arc forms, current increases some but voltage drops more, thus higher consumption of capacitor energy with little increase in energy deposited in gas**
- **Ratio of corona to arc energy very pressure-dependent)**

Corona discharges are energy-efficient

- **Discharge efficiency η_d much higher for corona or corona + arc than for conventional sparks**

$$\eta_d = \frac{\text{Energy deposited in gas}}{\text{Electrical discharge energy}} = \frac{\Delta P \cdot Volume \big/ \gamma - 1}{\int IVdt}$$

Discharge type	ΔP (psi)	Deposited energy	Electrical energy (mJ)	Efficiency
Spark	0.001531	2.7	54.0	0.050
Corona	0.005429	9.6	14.7	0.657
Corona+Arc	0.023853	42.4	68.0	0.623

3.5 atm tests

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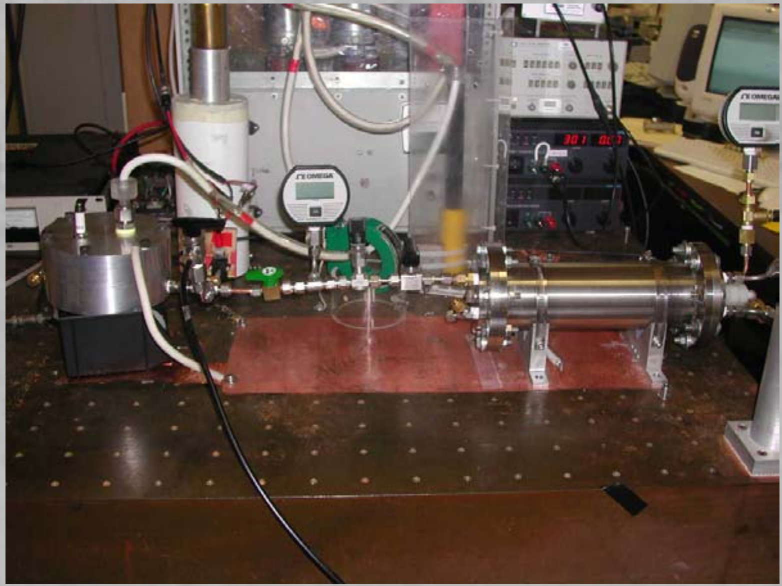
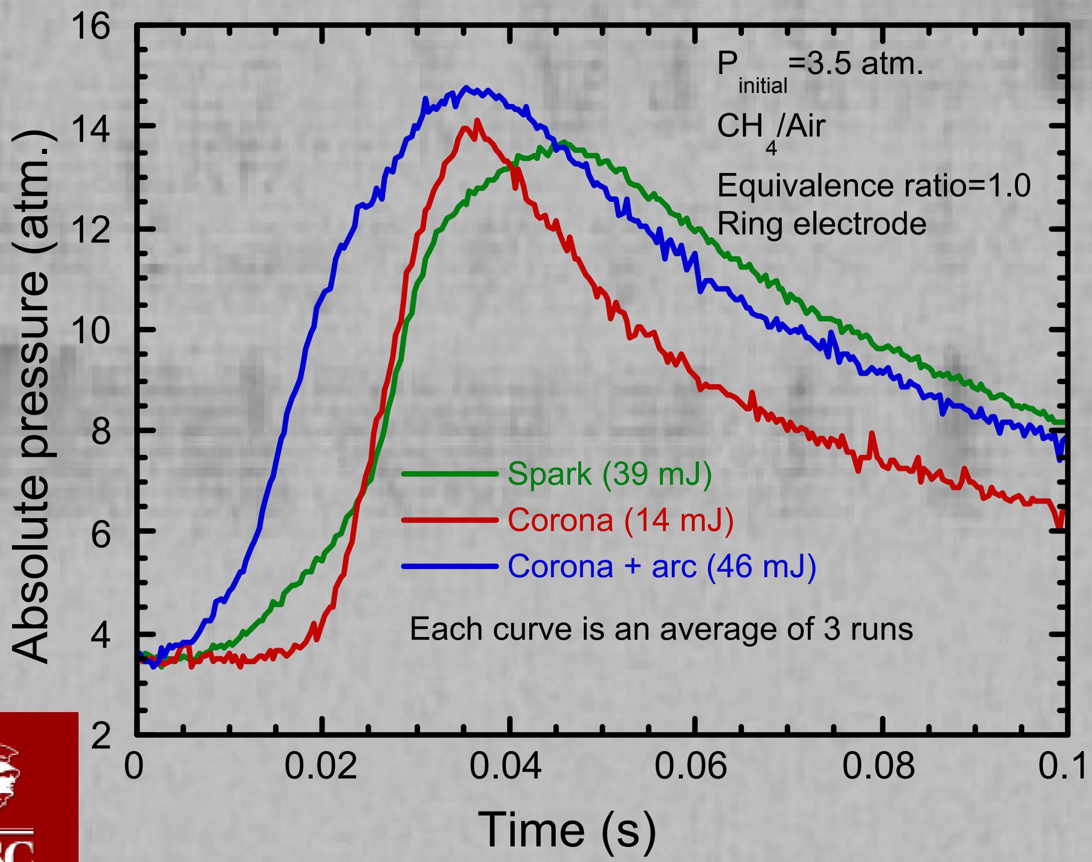
High-pressure corona ignition tests in simulated engine chamber

- **Perform combustion tests in sealed chamber at high initial pressures relevant to engine conditions**
- **Compare pressure and rise time between spark and corona at identical conditions**



Flame ignition by pulsed corona discharges in simulated engine chamber

- Delay time actually longer with corona in this geometry (but can be compensated by spark advance)
- Rise time 2x faster with corona, with far lower energy input
- Have ignited with corona only (no arc) up to 10 atm



Discharge type	Delay time (ms)	Rise time (ms)
Corona	20	10
Corona + arc	9	19
Spark	13.2	19

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Summary

- **Pulsed corona discharge ignition is a promising technology for improved efficiency & emissions performance in stationary NG engines**
  - Shorter pressure rise times - faster burning - exploit by
    - Burn leaner
    - More water injection
    - Lower turbulence levels
  - Energy efficiency
  - Electrode lifetime
  - Post-combustion NO_x reduction
- **Reasons for improvements not yet fully understood**
  - Geometrical - more distributed ignition sites? (Probably)
  - Chemical effects - more efficient use of electron energy? (Seems to be less important)

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Prior work: Diesel NO reduction via pulsed corona discharges

- **Energy efficient: ≈ 10 eV/molecule or less possible**
  - Transient plasma provides dramatically improved energy efficiency - by 100x compared to prior approaches employing quasi-steady discharges
  - 10 eV/molecule corresponds to 0.2 % of fuel energy input per 100 ppm NO destroyed

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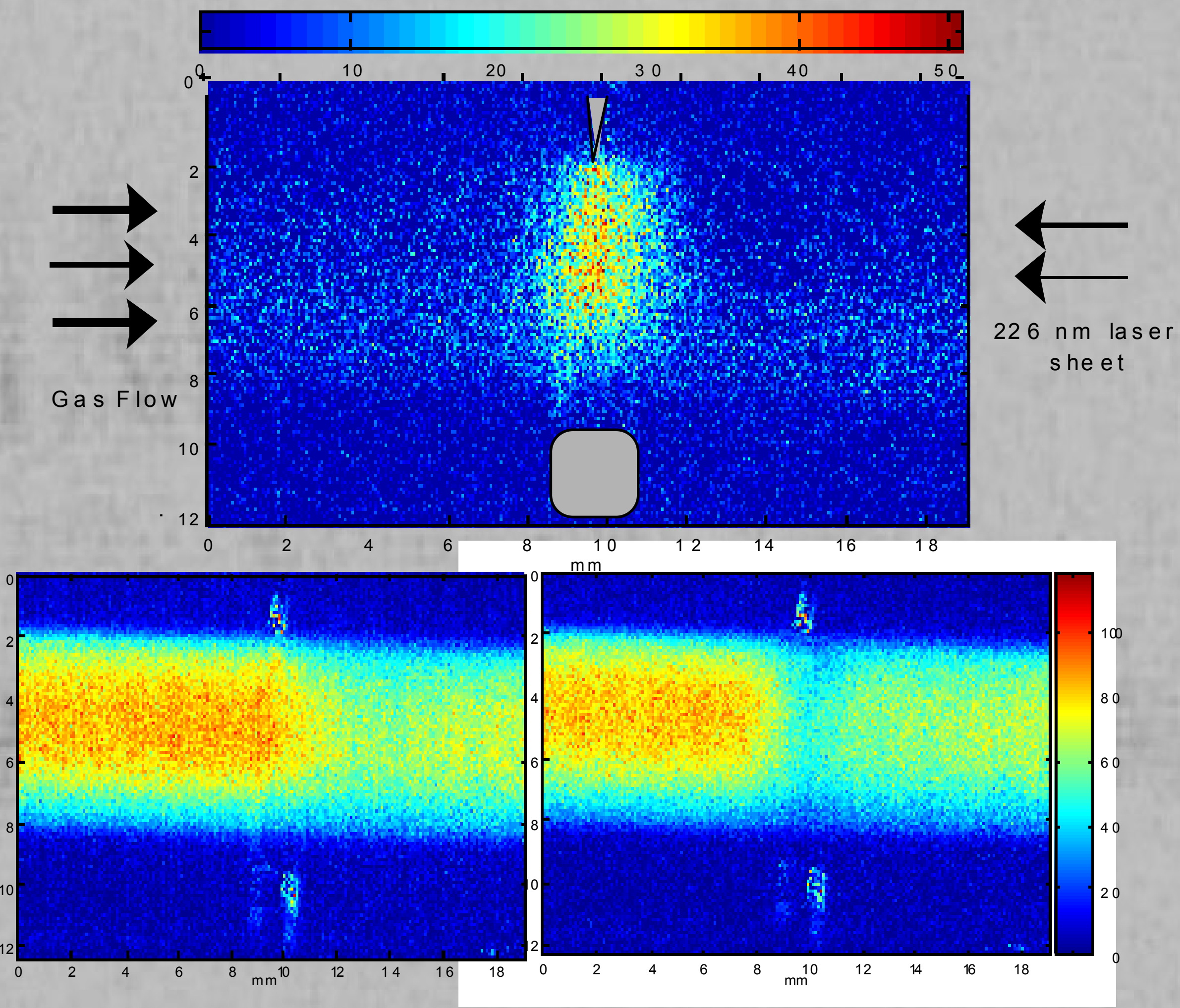
NO removal by corona discharge

- Diesel engine exhaust
- Needle/plane corona discharge (20 kV, 30 nsec pulse)
- Lower left: before pulse
- Lower right: 10 ms after pulse
- Upper: difference, showing single-pulse destruction of NO (≈ 40%)



Next steps

- Turbulent flame ignition
- Finish electrode optimization
- In-cylinder testing
- Need collaboration with NG engine manufacturer for full-scale engine testing

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Project Team & Capability

- **Co-investigator**
  – Prof. Martin A. Gundersen, Chair, USC Dept. of Electrical Engineering / Electrophysics
- **Research Professor**
  – Prof. Jian-Bang Liu
- **Graduate student & motorhead**
  – Nathan Theiss
- **Undergraduates**
  – Roberto Ortiz-Soto
  – Brandon Jones
  – Brad Tallon
  – Gary Norris

QUESTIONS?


Corona
Extra
Corona
Extra
LA CERVEZA MAS FINA
Brewed and bottled by
CERVECERIA MODELO, S.A. DE CV
MEXICO, D.F.